# FREQUENCY ESTIMATOR USING ARTIFICIAL NEURAL NETWORK FOR ELECTRICAL POWER SYSTEM DYNAMICS

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*Specially dedicated to my LOVE,*
*Thanks for the encouragement and endless support*
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# ABSTRACT

System frequency is a vital indicator for many applications in electrical power system dynamics. Therefore, an accurate and fast estimation of system frequency is important task since it is prerequisite for rapid-response applications such as in load shedding design, generator protection and renewable energy control. This thesis proposes an Artificial Neural Network (ANN) as a new estimator for frequency estimation in power system dynamics. In order to perform the ANN, power flow solution is obtained first for the system to be studied. The purpose of load flow simulation is to get some operating parameters which have the most influences on the system frequency behaviour. Then, a dynamic simulation is done by using a DigSILENT Power Factory Simulator to analyse frequency behaviours of the system by considering different operation conditions and types of disturbances that occur in the system (i.e. load injection, load rejection and generation outage). Simulations were carried out on the IEEE 9-Bus Test System and IEEE 39-Bus Test System (New England). The most relevant variables were selected as inputs to the ANN that were taken from data generated by dynamic simulator. Meanwhile, the ANN output is the undershoot frequency or overshoot frequency. Besides, the Lavernberg–Marquardt optimization with very fast propagation algorithm has been adopted for training feed–forward Neural–Network. The performances of the ANN were evaluated by using Mean Square Error and Regression analysis. To verify the effectiveness of the proposed approach, the results were compared with conventional methods in terms of estimation error and computation time. Therefore, the ANN has a great potential in real-time application since it provides a good accuracy (small error), fast and easy implementation.

# ABSTRAK

Frekuensi sistem merupakan penunjuk yang penting untuk kebanyakan aplikasi di dalam sistem elektrik kuasa dinamik. Oleh itu, ketepatan dan kepantasan menganggar frekuensi merupakan tugas yang penting memandangkan ia adalah prasyarat kepada aplikasi tindak balas yang pantas seperti merancang beban, perlindungan penjana dan mengawal tenaga yang boleh diperbaharui. Tesis ini mencadangkan Rangkaian Neural Buatan (ANN) sebagai penganggar baru untuk menganggar frekuensi di dalam sistem kuasa dinamik. Dalam usaha untuk membangunkan ANN, penyelesaian aliran kuasa diperolehi terlebih dahulu untuk sistem yang akan dikaji. Tujuannya ialah untuk mendapatkan beberapa parameter operasi yang paling mempengaruhi kelakuan frekuensi sistem. Kemudian, penyelaku dinamik sistem kuasa dilaksanakan oleh *'DigSILENT Power Factory Simulator'* untuk menganalisa tingkah laku frekuensi sistem dengan mengambil kira keadaan operasi yang berbeza dan jenis-jenis gangguan (misalnya pertambahan beban, pengurangan beban dan penjanaan lumpuh). Kajian simulasi telah dijalankan ke atas Sistem Ujian IEEE 9-Bas dan Sistem Ujian IEEE 39-Bas (New England). Pembolehubah-pembolehubah yang paling berkaitan yang diambil daripada penghasilan data oleh penyelaku dinamik telah dipilih sebagai input kepada ANN. Sementara itu, output ANN ialah frekuensi terendah dan frekuensi tertinggi. Di samping itu, Pengoptimuman *'Lavernberg-Marquardt'* menggunakan algoritma rambatan sangat pantas telah diterima pakai untuk latihan galakan hadapan Rangkaian Neural. Pelaksanaan ANN dinilai dengan menggunakan Min Ralat Kuasa Dua dan analisis Regresi. Untuk mengesahkan keberkesanan kaedah yang dicadangkan, hasil keputusan telah dibandingkan dengan kaedah-kaedah konvensional dari segi ralat penganggaran dan masa pengiraan. Oleh itu, ANN mempunyai potensi yang cerah bagi aplikasi masa sebenar memandangkan ia memberikan ketepatan baik (ralat yang kecil), pantas dan pelaksanaan yang mudah.

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| | | |
|---|---|---|
| AGC | - | Automatic Generation Control |
| ANF | - | Adaptive Notch Filter |
| ANN | - | Artificial Neural Network |
| DC | - | Direct Current |
| DFEA | - | Dynamic Frequency Estimation Algorithm |
| DFT | - | Discrete Fourier Transforms |
| DWT | - | Discrete Wavelet Transform |
| FIR | - | Finite Impulse Response |
| HYGOV | - | Governor system for hydro unit type |
| Hz | - | Hertz |
| IEC | - | International Electrotechnical Commission |
| IEEE | - | Institute of Electrical and Electronic Engineers |
| IEEEG1 | - | Governor system for steam unit type 1 |
| IEEEG3 | - | Governor system for hydro unit type 3 |
| LES | - | Least Mean Error |
| LMS | - | Least Mean Square |
| MSE | - | Mean Square Error |
| MVAr | - | Reactive power |
| MW | - | Mega Watt |
| PBFE | - | Phasor-based Frequency Estimation |
| PLL | - | Phase Locked Loop |
| R | - | Regression correlation coefficient |
| RMS | - | Root Mean Square |

| | | |
|---|---|---|
| SR | - | Spinning Reserve |
| UFLS | - | Under Frequency Load Shedding |
| USA | - | United States of America |

# LIST OF SYMBOLS

| | | |
|---|---|---|
| % | - | Percentage |
| $P_G$ | - | Real Power Generator |
| $P_L$ | - | Real Power Load |
| $P_{LOSS}$ | - | Real Power Loss |
| $\beta$ | - | Frequency sensitivity index |
| $f_{min}$ | - | Frequency minimum |
| $f_{max}$ | - | Frequency minimum |
| $X_d$ | - | Unsaturated *d*-axis synchronous reactance |
| $X_q$ | - | Unsaturated *q*-axis synchronous reactance |
| $X'_d$ | - | Unsaturated *d*-axis transient reactance |
| $X'_q$ | - | Unsaturated *q*-axis transient reactance |
| $X''_d$ | - | Unsaturated *d*-axis subtransient reactance |
| $X''_q$ | - | Unsaturated *q*-axis subtransient reactance |
| $T'_{do}$ | - | *d*-axis transient open circuit time constant |
| $T'_{qo}$ | - | *q*-axis transient open circuit time constant |
| $T''_{do}$ | - | *d*-axis subtransient open circuit time constant |
| $T''_{qo}$ | - | *q*-axis subtransient open circuit time constant |
| $X_l$ | - | Leakage or Potier reactance |
| $H$ | - | Inertia constant |
| pu | - | Per unit |
| $s$ | - | Second |
| K | - | Controller Gain |
| T1 | - | Governor Time Constant |

| | | |
|---|---|---|
| T2 | - | Governor Derivetive Time |
| T3 | - | Servo Time Constant |
| K1 | - | High Pressure Turbine Factor |
| K2 | - | High Pressure Turbine Factor |
| T5 | - | Intermediate Pressure Turbine Time Constant |
| K3 | - | Intermediate Pressure Turbine Factor |
| K4 | - | Intermediate Pressure Turbine Factor |
| T6 | - | Medium Pressure Turbine Time Constant |
| K5 | - | Medium Pressure Turbine Factor |
| K6 | - | Medium Pressure Turbine Factor |
| T4 | - | High Pressure Turbine Time Constant |
| T7 | - | Low Pressure Turbine Time Constant |
| K7 | - | Low Pressure Turbine Factor |
| K8 | - | Low Pressure Turbine Factor |
| Delta | - | Participation Factor |
| Uc | - | Valve Closing Time |
| Pmin | - | Minimum Gate Limit |
| Uo | - | Valve Opening Time |
| Pmax | - | Maximum Gate Limit |
| $R_P$ | - | Permanent Droop |
| $R_T$ | - | Temporary Doop |
| Tr | - | Governor Time Constant |
| Tf | - | Filter Time Constant |
| Tg | - | Servo Time Constant |
| Tw | - | Water Starting Time |
| At | - | Turbine Gain |
| Pturb | - | Turbine Rated Power (0= pturb =pgen) |
| Dturb | - | Frictional Losses Factor pu |
| Qnl | - | No Load Flow |
| Gmin | - | Minimum Gate Limit |

| | | |
|---|---|---|
| Qnl | - | No Load Flow |
| Velm | - | Gate Velocity Limit |
| Gmax | - | Maximum Gate Limit |
| Tg | - | Gate Servomotor Time Constant |
| Delta | - | Participation Factor |
| Tp | - | Pilot Valve Time Constant |
| Sigma | - | Permanent Droop |
| Delta | - | Temporary Droop |
| Tr | - | Governor Time Constant |
| a11 | - | Waterhammer 1th Factor |
| a13 | - | Waterhammer 2th Factor |
| a21 | - | Waterhammer 3th Factor |
| a23 | - | Waterhammer 1th Factor |
| Tw | - | Water Starting |
| Pturb | - | Turbine Rated Power (0=pturb=pgen) |
| Uc | - | Valve Closing Time |
| Pmin | - | Minimum Gate Limit |
| Uo | - | Valve Opening Time |
| Pmax | - | Maximum Gate Limit |

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# CHAPTER 1

# INTRODUCTION

## 1.1 Frequency in Power System

A power system is predominantly in steady state operation or in a state that could with sufficient accuracy be regarded as steady state [1]. Under steady state conditions the total power generated by power stations is equal to the system load and losses, while frequency normally operated at a nominal value. Typically, the nominal frequency is assumed to be 50 Hz as in the ENTSO-E Continental Europe system (formerly UCTE) [2] and Malaysia standard (MS IEC 60038). Frequency is regarded as a paramount index of the operation of power systems because it can reflect the dynamic energy balance situation between generating power and load [3,4]. Therefore, the frequency is the basis indicator for monitoring of other electrical variables [5].

System frequency is normally maintained at nominal value when the same amount of electrical power produced is consumed by the loads and including system losses [1]. It can also be noted that the frequency is the same in the whole system at steady state condition, provided that the balance between real power generator and demand is met. Thus, the frequency of power system is dependent on real power balance.

During normal operating conditions, the system frequency does not deviate much from its nominal value. Normal operational practice in Malaysia is to keep frequency deviations in range of ± 1% of the nominal value. Practically, the permitted stationary frequency deviation for the system operation is established as 50 ± 0.5 Hz [6] including Malaysia, i.e. 49.5 – 50.5 Hz range. Beyond these limits may result abnormal conditions of electrical power system.

However, a change in real power demand at one point of a network is reflected throughout the system by a change in frequency. Besides, the frequency may deviate from the set point value either due to a generation surplus or a generation deficit within the whole system which has an accelerating or decelerating effect on the synchronous machines [1]. In short, the frequency varies from its nominal value due to the transient events occurred in the power system dynamics. A dynamic phenomenon in a power system is initiated by a disturbance. Therefore, the response of the system after disturbance occurred depend on a how large the disturbance is [3].

The frequency of the system is reduced when a load increase is not compensated for by a corresponding increase of the turbine power of the connected generators. The power deficit decelerates the generator rotors and consequently the frequency is reduced. Frequency reductions also arise when production is lost, e.g. as a consequence of failures in the system which lead to that protections disconnect the failed equipment [1]. A load reduction in the system which is not compensated for by a reduction of turbine power leads to a frequency increase. These behaviors of a power system dynamics is summarized as shown in Table 1.1

**Table 1.1:** Behavior of power system frequency

| System Condition | System Frequency |
|---|---|
| $P_G > P_L + P_{LOSS}$ | Increase |
| $P_G = P_L + P_{LOSS}$ | No change |
| $P_G < P_L + P_{LOSS}$ | Decrease |

A non-nominal frequency causes a lower quality of the delivered electrical energy. A large frequency deviation would degrade load performance, cause the transmission lines to be overloaded, also could interfere with system protection schemes and control [7]. Further, too large frequency deviation would damage equipment, since a lot of equipment in the power stations, e.g. power supply systems, cannot tolerate very low frequencies.

Furthermore, the worst case when there are very low frequencies (lower than 48Hz) [2,3] can lead to damaging vibrations in steam turbines which has to be disconnected. This constitutes an even worse stress on the system ultimately leading to a complete power system collapse [2,3]. In comparison with the thermal units, hydro power plants are more robust and can normally cope with frequency down to 45 Hz [1]. In short, off-nominal frequency can directly impact on power system operation and system reliability [3]. An example a normal and abnormal frequency range of power system (i.e. 60 Hz) for United States of America (USA) and Canadian system are illustrated in Figure 1.1[7].

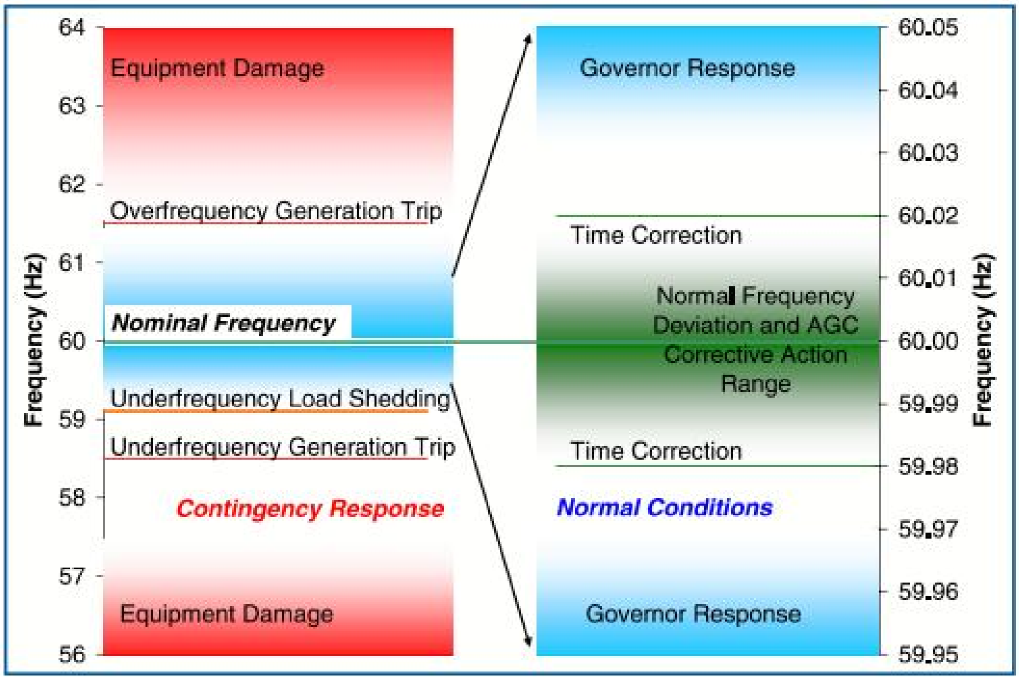


**Figure 1.1** Normal and abnormal frequency range

## 1.2 Problem Statement

The major problem of an electric power system dynamics is due to disproportion between generated powers and loads. This might leads to instability in the power system, and hence resulting to a black out. Imbalance between generated powers and loads will be affected on frequency variation.

The estimating frequency is an important task in the power system operation, monitoring, control and protection. Frequency estimation is one of the requirements for under frequency protection system design such as Under Frequency Load Shedding (UFLS). Based on this fact the most important automatic control schemes use the system frequency as a main input variable. The estimated frequency is used to design load shedding accurately to correct frequency back to an acceptable threshold.

A conventional simulator would require unrealistic hours of computational time for all possible dynamic system scenarios. A simulation for a large case data will degrade the performance in terms of slow computational. Many evaluation of the dynamic behavior of a system need a rapid response, like the case of planning a load shedding scheme [9]. Therefore, a new frequency estimator using ANN is proposed in this research to deal with this problem due to the ability to provide fast response with sufficient accuracy.

## 1.3 Objectives of Research

The objectives of this research study are to:

i) Develop dynamic simulator for frequency response of the system.

ii) Develop an ANN for frequency estimation in power system dynamics.

iii) Compare results between ANN and dynamic simulator (conventional method) in terms of error accuracy (MSE) and computational time.

## 1.4 Scope of Research

The scopes of this research are:

i) IEEE 9-Bus Test System for a small case study and IEEE 39-Bus Test System (New England) for a large scale system.
ii) Developing dynamic simulations using DIgSILENT Power Factory Simulator of the test system.
iii) Estimate undershoot and overshoot frequency, i.e. minimum frequency ($f_{min}$) and maximum frequency ($f_{max}$)
iv) Types of disturbance considered are load injection, load rejection and generator outage.
v) Using Matlab's software (ANN toolbox) for frequency estimation.

## 1.5 Contributions of Research

The main contributions of this research are:

i) Developing an ANN based dynamic simulator for electrical power systems.
ii) Application of new approach to estimate the frequency dynamics of the power system within different operation scenarios.
iii) Simulation studies (case studies) have been performed for different scale of test systems.

## 1.6 Thesis outline

This thesis consists of 5 chapters. Chapter I discusses about the introduction with regards to frequency in power systems, problem statement, objectives of research, scope of research and contributions of research.

Chapter 2 discusses a literature review of previous work that has been done. It discusses about frequency estimation methods in power system such as Probabilistic Technique, Signal Processing Techniques and Artificial Intelligence Techniques. The limitations of previous method and a proposed new technique are also discussed.

In Chapter 3, the discussion will be on the methodology of this project. It contains the procedure of research such as power flow calculation in steady state condition, procedure of dynamic simulation (time-domain simulation) when a disturbance is considered to be occurred into the system studied. Both simulations for load flow and dynamic are done by using a conventional simulator, DIgSILENT Power Factory Simulator. Then, MATLAB is used for ANN implementation based on similar cases of dynamic simulations to estimate frequency in power system dynamics. The approached method is applied on the IEEE 9-Bus Test System. The similar procedure therefore is applied on the IEEE 39-Bus Test System for a larger scale system.

The result, analysis and discussion will be presented in Chapter 4. It is based on load flow result, time-domain simulation and application of ANN for frequency response in power system dynamics. The comparisons between conventional simulator and ANN have been made. The ANN shows some advantages in term of error estimation, computation time and easy implementation as compared to conventional method. The last chapter, Chapter 5 concludes this research and recommendation for future research.

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